Migration of trans-Neptunian objects to a near-Earth space

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Our estimates of the migration of trans-Neptunian objects (TNOs) to a near-Earth space are based on the results of investigations of orbital evolution of TNOs and Jupiter-crossing objects (JCOs). The orbital evolution of TNOs was considered in many papers [1-2, etc.]. Recently we investigated the evolution for intervals of at least 5-10 Myr of 2500 JCOs under the gravitational influence of all planets, except for Mercury and Pluto (without dissipative factors). In the first series we considered N=2000 orbits near the orbits of 30 real Jupiter-family comets with period P_a<10 yr, and in the second series we took N=500 orbits close to the orbit of Comet 10P Tempel 2 ($a\approx 3.1$ AU, $e\approx 0.53$, $i\approx 12^{\circ}$). We calculated the probabilities of collisions of objects with the terrestrial planets, using orbital elements obtained with a step equal to 500 yr, and then summarized the results for all time intervals and all bodies, obtaining the total probability P_Σ of collisions with a planet and the total time interval T_Σ during which perihelion distance q of bodies was less than a semimajor axis of the planet. We used formulas, which were obtained by us for the first time, for the case when a body moves with a variable velocity in its orbit. The values of $P_r=10^6 P_\Sigma/N=10^6 P$ and $T_r=T/1000$ yr (where $T=T_\Sigma/N$) are presented in the Table together with the ratio r of the total time interval when orbits were of Apollo type (at a>1 AU, $q=a(1-e)$<1.017 AU, e<0.999) to that of Amor type (1.017<q<1.33 AU). At e<0.9, r=1.15 for N=2000 and r=1.34 for N=500. Note that for asteroids from the resonances 3:1 and 5:2 with Jupiter we also got r>1 (1.9 and 1.3, respectively). For observed near-Earth objects (NEOs) r is close to 1.

Table	Venus	Venus	Earth	Earth	Mars	Mars	-
N	P_r	T_r	P_r	T_r	P_r	T_r	r
2000	6.62	9.3	6.65	14.0	2.03	24.7	1.32
500	16.3	24.9	24.5	44.0	5.92	96.2	1.49

We found several bodies that moved for more than 1 Myr in orbits with aphelion distance Q<4.7 AU. The time interval during which a body had Q less than 3.2 and 3.7 AU exceeded 0.1 and 2.6 Myr, respectively. We believe that this is the first time that this effect has been found. Most of the collisions of former JCOs with the Earth were from orbits with aphelia inside Jupiter's orbit. The probability of collisions with the Earth for 3 former JCOs, each of which moved for more than 1 Myr in Earth-crossing orbits (mainly with Q<4.7 AU) was 1.5 times greater than that for the other 1997 JCOs. About 1 of 300 JCOs collided with the Sun. For 2000 JCOs we considered, the mean probability of collisions with Venus was about the same as with Earth, and that with Mars was smaller by a factor of 3. These values were mainly due to a few bodies that moved during more than 1 Myr in orbits with aphelia deep inside Jupiter's orbit (for such bodies usually more than 80% of collisions with planets were from orbits with Q<4.2 AU). If we consider 1000 JCOs, for which most of the collisions with planets were from orbits with Q>4.2 AU, then the mean probability for Venus and Mars is less by a factor of 1.6 and 3, respectively, than that for Earth. Therefore, the ratio of the total mass of icy planetesimals that migrated from the feeding zone of the giant planets and collided with the planet to the mass of this planet was greater for Mars than that for Earth and Venus. The total time during which former 2000 JCOs were in Apollo-type and Amor-type orbits was 28.7 and 21.75 Myr, respectively, but 12.7 and 11.4 Myr of the above times were due to three objects.

The mean time during which an object crossed Jupiter's orbit was 0.13 Myr for 2500 considered JCOs. An object had period P_a<10 yr usually only during about 12% of this time, so we think that our consideration of initial objects with only P_a<10 yr does not influence much on the results of evolution of JCOs. At N=2000 for 10<P_a<20, 20<P_a<50, 50<P_a<200 yr, we got

23%, 22% and 16%, respectively. One former JCO spent some time in orbits with aphelia deep inside Jupiter's orbit, and then it moved for tens of Myr in the trans-Neptunian region, partly in low eccentricity and partly in high eccentricity orbits. This result shows that some main-belt asteroids can move into the trans-Neptunian region, and that typical TNOs can become scattered disk objects (with high eccentricities) and vice versa.

For integrations we used the Bulirsh-Stoer method (BULSTO) and a symplectic method. The probabilities of collisions of former JCOs with planets were close for these methods, but bodies got resonant orbits more often in the case of BULSTO. For asteroids initially located at the 3:1 resonance with Jupiter, we found that the ratio r_{hc} of the number of asteroids ejected into hyperbolic orbits to that collided the Sun was equal to 5.6 for BULSTO and to 0.38 and 0.87 for a symplectic method for a step of integration equal to 10 and 30 days, respectively. So in some cases a symplectic method can give a large error. For the 5:2 resonance with Jupiter, r_{hc} equaled 20 and 10 for BULSTO and symplectic methods, respectively.

The number of TNOs migrating to the inner regions of the Solar System can be evaluated on the basis of simple formulas and the results of numerical integration. Let $N_J=P_N \cdot p_{JN} \cdot N_{TNO}$ be the number of former TNOs with $d>D$ reaching Jupiter's orbit for the given time span T_{SS}, where N_{TNO} is the number of TNOs with $d>D$; P_N is the fraction of TNOs leaving the trans-Neptunian belt and migrating to Neptune's orbit during T_{SS}; and p_{JN} is the fraction of Neptune-crossing objects which reach Jupiter's orbit for their lifetimes. Then the current number of Jupiter-crossers that originated in the zone with $30<a<50$ AU equals $N_{Jn}=N_J \Delta t_J/T_{SS}$, where Δt_J is the average time during which the object crosses Jupiter's orbit. According to [1], the fraction P_N of TNOs that left this zone during T_{SS}=4 Gyr under the influence of the giant planets is 0.1-0.2 and p_{JN}=0.34. As mutual gravitational influence of TNOs also takes place [2], we take P_N=0.2. Hence, at Δt_J=0.13 Myr and $N_{TNO}=10^{10}$ (d>1 km), we have $N_{Jn}=2 \cdot 10^4$. The number of former TNOs now moving in Earth-crossing orbits equals $N_E=N_{Jn}T/\Delta t_J$. For T=0.014 Myr and Δt_J=0.13 Myr, we have N_E=2150. It is larger than the estimated number of Earth-crossers with d>1 km (750). Such difference can be caused by the fact that this number doesn't include NEOs with large values of e and i. It is also probable that the number of 1-km TNOs is smaller by a factor of several than 10^{10}. The number of former TNOs which now have Amor-type orbits is smaller by a factor of r=1.3 than N_E.

The total mass of water delivered to the Earth during formation of the giant planets is $M_w=M_J P_{JE} k_i$, where M_J is the total mass of planetesimals from the feeding zones of these planets that got Jupiter-crossing orbits during evolution, P_{JE} is a probability P of a collision of a JCO with the Earth during its lifetime, and k_i is the portion of water ices in planetesimals. For $M_J=100m_\oplus$ (where $m_\oplus$ is the mass of the Earth), k_i=0.5, and $P_{JE}=6.65 \cdot 10^{-6}$, we have $M_w=3.3 \cdot 10^{-4} \cdot m_\oplus$. This value is greater by a factor of 1.5 than the mass of the Earth oceans. The mass of water delivered to Venus can be of the same order of magnitude and that delivered to Mars can be less by a factor of 3. Some TNOs with a>50 AU can also migrate to the orbits of Jupiter and Earth. Former JCOs can also decrease their aphelia due to collisions with small bodies and to other nongravitational forces. So the values of P_r and T_r can be larger than those in the Table. As it is easier to destroy icy bodies than stone or metal bodies, the portion of TNOs among near-Earth objects for bodies with d<100 m (for example, for Tunguska-size bodies) may be greater than that for 1-km bodies, but small icy bodies disappear in the atmosphere. This work was supported by NASA grant NAG5-10776, INTAS (00-240) and RFBR (01-02-17540).

[1] Duncan, M. J., H. F. Levison, and S. M. Budd, *Astron. J.*, **110**, 3073-3081 (1995);

[2] Ipatov, S.I., *Advances in Space Research*, Elsevier, **28**, N 8, 1107-1116 (2001) (http://arXiv.org/format/astro-ph/0108187).